



Improved Evidence for Direct CP Violation in $B^0 \rightarrow \pi^+ \pi^-$ Decays and Model-Independent Constraints on ϕ_2

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Abstract

We present a new measurement of the time-dependent CP -violating parameters in $B^0 \rightarrow \pi^+\pi^-$ decays with 275×10^6 $B\bar{B}$ pairs collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider operating at the $\Upsilon(4S)$ resonance. We find 666 ± 43 $B^0 \rightarrow \pi^+\pi^-$ events and measure the CP -violating parameters: $\mathcal{S}_{\pi\pi} = -0.67 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$ and $\mathcal{A}_{\pi\pi} = +0.56 \pm 0.12(\text{stat}) \pm 0.06(\text{syst})$. We find evidence for large direct CP -violation with a significance greater than 4 standard deviations for any $\mathcal{S}_{\pi\pi}$ value. Using isospin relations, we obtain 95.4% confidence intervals for the CKM angle ϕ_2 of $0^\circ < \phi_2 < 19^\circ$ and $71^\circ < \phi_2 < 180^\circ$.

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One of the unresolved mysteries in particle physics is the origin of CP violation. Kobayashi and Maskawa (KM) pointed out in 1973 that CP violation can be incorporated as an irreducible complex phase in the weak-interaction quark mixing matrix in the standard model (SM) framework [1]. The KM model predicts CP -violating asymmetries in the time-dependent rates of neutral B meson decays to the CP eigenstate $\pi^+\pi^-$ [2]. In the decay chain of $\Upsilon(4S) \rightarrow B^0\bar{B}^0 \rightarrow (\pi^+\pi^-)(f_{\text{tag}})$, one of the neutral B mesons decays into $\pi^+\pi^-$ at time $t_{\pi\pi}$ and the other decays at time t_{tag} to a final state f_{tag} that distinguishes its flavor. The time-dependent decay rate is given by

$$\mathcal{P}_{\pi\pi}^q(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} [1 + q \cdot \{\mathcal{S}_{\pi\pi} \sin(\Delta m_d \Delta t) + \mathcal{A}_{\pi\pi} \cos(\Delta m_d \Delta t)\}], \quad (1)$$

where $\Delta t = t_{\pi\pi} - t_{\text{tag}}$, τ_{B^0} is the B^0 lifetime, Δm_d is the mass difference between the two neutral B mass eigenstates, and $q = +1$ (-1) for $f_{\text{tag}} = B^0$ (\bar{B}^0). We measure $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$, which are the mixing-induced and direct CP -violating parameters, respectively. In the case where only a $b \rightarrow u$ tree transition contributes to the decay $B^0 \rightarrow \pi^+\pi^-$ [3], we would have $\mathcal{S}_{\pi\pi} = \sin 2\phi_2$ and $\mathcal{A}_{\pi\pi} = 0$. Because of possible contributions from $b \rightarrow d$ penguin transitions that have different weak and strong phases, $\mathcal{S}_{\pi\pi}$ may deviate from $\sin 2\phi_2$, and direct CP violation, $\mathcal{A}_{\pi\pi} \neq 0$, may occur. Our previous measurement based on a 140 fb^{-1} data sample indicated large $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ values [4], while no significant CP asymmetry was observed by the BaBar Collaboration [5]. It is therefore important to measure the CP -violating parameters with larger statistics.

The measurement in this Letter is based on a 253 fb^{-1} data sample containing $275 \times 10^6 B\bar{B}$ pairs collected with the Belle detector at the KEKB e^+e^- asymmetric-energy (3.5 on 8 GeV) collider [6] operating at the $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ is produced with a Lorentz boost factor of $\beta\gamma = 0.425$ along the z axis, which is antiparallel to the positron beam direction. Since the two B mesons are produced nearly at rest in the $\Upsilon(4S)$ center-of-mass system (CMS), the decay time difference Δt is determined from the distance between the two B meson decay positions along the z -direction (Δz): $\Delta t \cong \Delta z/c\beta\gamma$, where c is the velocity of light.

The Belle detector [7] is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). A sample containing $152 \times 10^6 B\bar{B}$ pairs (Set I) was collected with a 2.0 cm radius beampipe and a 3-layer silicon vertex detector, while a sample with $123 \times 10^6 B\bar{B}$ pairs (Set II) was collected with a 1.5 cm radius beampipe, a 4-layer silicon detector, and a small-cell inner drift chamber [8].

We reconstruct $B^0 \rightarrow \pi^+\pi^-$ candidates using oppositely charged track pairs that are positively identified as pions by combining information from the ACC and the CDC dE/dx measurements. The pion detection efficiency is 90%, and 11% of kaons are misidentified as pions. We select B meson candidates using the energy difference $\Delta E \equiv E_B^* - E_{\text{beam}}^*$ and the beam-energy constrained mass $M_{\text{bc}} \equiv \sqrt{(E_{\text{beam}}^*)^2 - (p_B^*)^2}$, where E_{beam}^* is the CMS beam-energy, and E_B^* and p_B^* are the CMS energy and momentum of the B candidate. We

define the signal region as $5.271 \text{ GeV}/c^2 < M_{bc} < 5.287 \text{ GeV}/c^2$ and $|\Delta E| < 0.064 \text{ GeV}$, which corresponds to ± 3 standard deviations (σ) from the central values.

We identify the flavor of the accompanying B meson from inclusive properties of particles that are not associated with the reconstructed $B^0 \rightarrow \pi^+\pi^-$ decay. We use q defined in Eq. (1) and r to represent the tagging information. The parameter r is an event-by-event, Monte Carlo (MC) determined flavor-tagging dilution factor that ranges from $r = 0$ for no flavor discrimination to $r = 1$ for unambiguous flavor assignment. It is used only to sort data into six r intervals. The wrong tag fractions for the six r intervals, w_l ($l = 1, 6$), and the differences between B^0 and \bar{B}^0 decays, Δw_l , are determined from data [9, 10].

To suppress the continuum background ($e^+e^- \rightarrow q\bar{q}; q = u, d, s, c$), we apply the technique used in Ref. [4]. We form a likelihood ratio LR based on event topology variables and impose requirements on LR to suppress continuum events. The LR requirement is determined by optimizing the expected sensitivity using MC signal events and events in the sideband region in $5.20 \text{ GeV}/c^2 < M_{bc} < 5.26 \text{ GeV}/c^2$ or $+0.1 \text{ GeV} < \Delta E < +0.5 \text{ GeV}$. As the tag-dilution variable r also suppresses continuum events, we optimize LR separately for each of the r bins. For all r bins we accept events having $LR > 0.86$; we then include additional events having lower LR thresholds of 0.50, 0.45, 0.45, 0.45, 0.45, and 0.20, respectively, for the six r bins. There are thus 12 distinct bins of LR - r for selected events.

We extract 2,820 signal candidates by applying the above requirements and the vertex reconstruction algorithm used in Ref. [10] to the data sample. Figure 1 shows the ΔE distributions for the events with (a) $LR > 0.86$ and (b) $LR < 0.86$ in the M_{bc} signal region. The $B^0 \rightarrow \pi^+\pi^-$ signal yield is determined from an unbinned two-dimensional maximum likelihood fit to the ΔE - M_{bc} distribution in the range of $M_{bc} > 5.20 \text{ GeV}/c^2$ and $-0.3 \text{ GeV} < \Delta E < +0.5 \text{ GeV}$ with signal events plus contributions from misidentified $B^0 \rightarrow K^+\pi^-$ events, the continuum background, and three-body B decays. We use a single Gaussian for the signal and $B^0 \rightarrow K^+\pi^-$ events in ΔE and M_{bc} . The continuum background shapes in ΔE and M_{bc} are described by a first-order polynomial and an ARGUS function [11], respectively. For the three-body B decay background shape, we employ a smoothed two-dimensional histogram obtained from a large MC sample. The fit to the subset with $LR > 0.86$ yields $415 \pm 27 \pi^+\pi^-$ events and $154 \pm 19 K^+\pi^-$ events in the signal region, where the errors are statistical only. The $K^+\pi^-$ contamination is consistent with the $K \rightarrow \pi$ misidentification probability, which is measured independently. Extrapolating from the size of the continuum background in this fit, we expect 315 ± 3 continuum events in the signal region. We use MC-determined fractions as in [4] to calculate the numbers of decays for $LR < 0.86$. We expect $251 \pm 16 \pi^+\pi^-$, $93 \pm 12 K^+\pi^-$ and $1,592 \pm 15$ continuum events in the signal region. The contribution from three-body B decays is negligibly small in the signal region.

We determine $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ by applying an unbinned maximum likelihood fit to the distribution of proper-time difference Δt . The probability density function (PDF) for the signal events is given in Eq. (1) modified to incorporate the effect of incorrect flavor assignment w_l and Δw_l . The distribution is convolved with the proper time interval resolution function $R_{\text{sig}}(\Delta t)$ in order to take into account the finite position resolution [10, 12]. The PDF for $B^0 \rightarrow K^+\pi^-$ is $\mathcal{P}_{K\pi}^q(\Delta t, w_l, \Delta w_l) = (1/4\tau_{B^0})e^{-|\Delta t|/\tau_{B^0}}[1 - q\Delta w_l + q(1 - 2w_l)\mathcal{A}_{K\pi}^{\text{eff}} \cos(\Delta m_d \Delta t)]$. We use $\mathcal{A}_{K\pi}^{\text{eff}} = (\mathcal{A}_{K\pi} + \mathcal{A}_\varepsilon)/(1 + \mathcal{A}_{K\pi}\mathcal{A}_\varepsilon)$, where $\mathcal{A}_{K\pi} = -0.109 \pm 0.019$ is the measured direct CP -violating parameter in $B^0 \rightarrow K^+\pi^-$ decays [13], and \mathcal{A}_ε is the difference in the product of the pion efficiency and kaon misidentification probability between $\pi^+(K^-)$ and $\pi^-(K^+)$ divided by their sum [14]. The inclu-

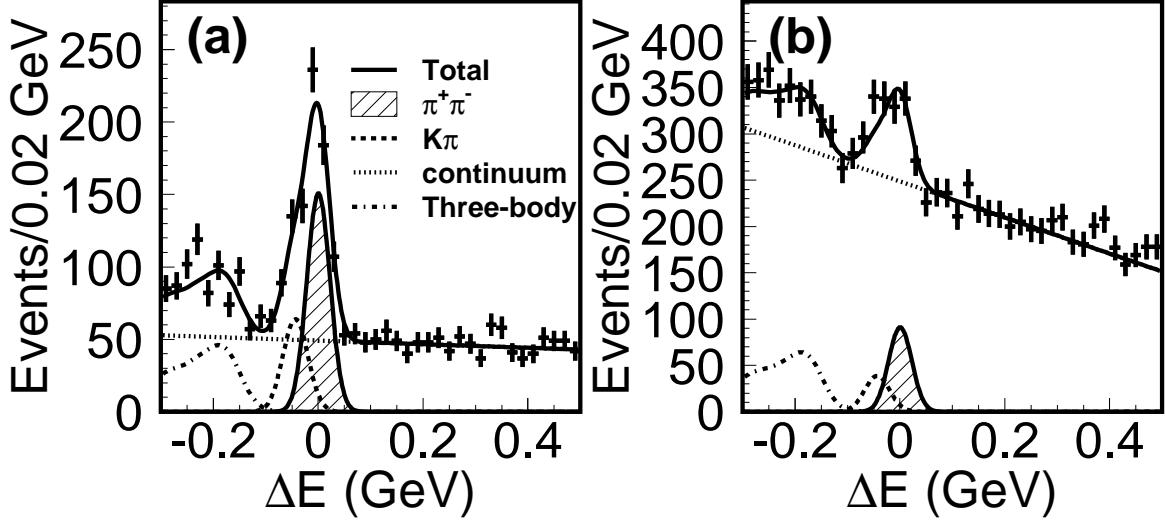


FIG. 1: ΔE distributions in the M_{bc} signal region for $B^0 \rightarrow \pi^+\pi^-$ candidates with (a) $LR > 0.86$ and (b) $LR < 0.86$.

sion of \mathcal{A}_ε changes the $\mathcal{A}_{K\pi}$ value by 11%. We make use of the same resolution function $R_{\text{sig}}(\Delta t)$ for the $B^0 \rightarrow K^+\pi^-$ events. The PDF for the continuum background events is $\mathcal{P}_{q\bar{q}}(\Delta t) = 1/2 \cdot (1 + q\mathcal{A}_{q\bar{q}})[(f_\tau/2\tau_{q\bar{q}})e^{-|\Delta t|/\tau_{q\bar{q}}} + (1 - f_\tau)\delta(\Delta t)]$, where f_τ is the fraction of the background with effective lifetime $\tau_{q\bar{q}}$, and δ is the Dirac delta function. We use $\mathcal{A}_{q\bar{q}} = 0$ as a default. A fit to the sideband events yields $\mathcal{A}_{q\bar{q}} = +0.01 \pm 0.01$ (-0.00 ± 0.01) for the data in Set I (II). This uncertainty in the background asymmetry is included in the systematic error for the $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ measurement. The background PDF $\mathcal{P}_{q\bar{q}}$ is convolved with a background resolution function $R_{q\bar{q}}$. All parameters in $\mathcal{P}_{q\bar{q}}$ and $R_{q\bar{q}}$ are determined from sideband events.

We define a likelihood value for each (i th) event as a function of $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$:

$$P_i = (1 - f_{\text{ol}}) \int_{-\infty}^{+\infty} [\{f_{\pi\pi}^m \mathcal{P}_{\pi\pi}^q(\Delta t', w_l, \Delta w_l; \mathcal{S}_{\pi\pi}, \mathcal{A}_{\pi\pi}) \\ + f_{K\pi}^m \mathcal{P}_{K\pi}^q(\Delta t', w_l, \Delta w_l)\} R_{\text{sig}}(\Delta t_i - \Delta t') \\ + f_{q\bar{q}}^m \mathcal{P}_{q\bar{q}}(\Delta t') R_{q\bar{q}}(\Delta t_i - \Delta t')] d\Delta t' \\ + f_{\text{ol}} \mathcal{P}_{\text{ol}}(\Delta t_i). \quad (2)$$

Here, the probability functions f_k^m ($k = \pi\pi, K\pi$, or $q\bar{q}$) are determined on an event-by-event basis as functions of ΔE and M_{bc} for each LR - r bin ($m = 1, 12$). A small number of signal and background events that have large values of Δt is accommodated by the outlier PDF, \mathcal{P}_{ol} , with a fractional area f_{ol} . In the fit, $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ are the only free parameters and are determined by maximizing the likelihood function $\mathcal{L} = \prod_i P_i$, where the product is over all the $B^0 \rightarrow \pi^+\pi^-$ candidates.

The unbinned maximum likelihood fit to the 2,820 $B^0 \rightarrow \pi^+\pi^-$ candidates containing 666 ± 43 $\pi^+\pi^-$ signal events (1,486 B^0 tags and 1,334 \bar{B}^0 tags) yields $\mathcal{S}_{\pi\pi} = -0.67 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$ and $\mathcal{A}_{\pi\pi} = +0.56 \pm 0.12(\text{stat}) \pm 0.06(\text{syst})$. The correlation between $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ is +0.09. In this Letter, we quote the usual fit errors from the likelihood functions, called the MINOS errors, as statistical uncertainties [15]. Figures 2(a) and 2(b)

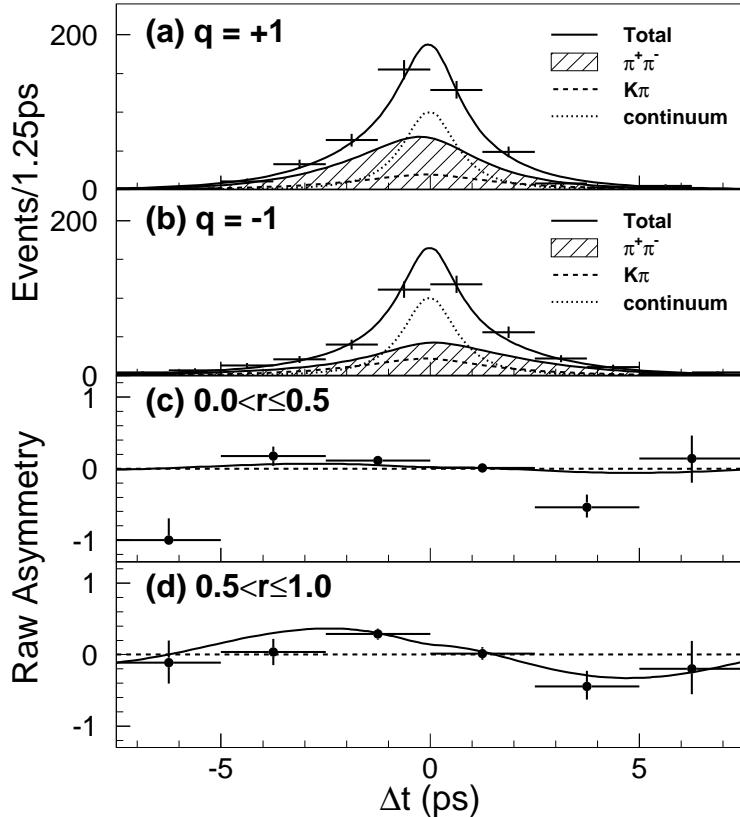


FIG. 2: Δt distributions for the 884 $B^0 \rightarrow \pi^+\pi^-$ candidates with $LR > 0.86$ in the signal region: (a) 470 candidates with $q = +1$, (b) 414 candidates with $q = -1$. Raw asymmetry, \mathcal{A}_{CP} , in each Δt bin with (c) $0 < r \leq 0.5$ and (d) $0.5 < r \leq 1.0$. The solid lines show the results of the unbinned maximum likelihood fit to the Δt distribution of the 2,820 $B^0 \rightarrow \pi^+\pi^-$ candidates.

show the Δt distributions for the 470 B^0 - and 414 \bar{B}^0 -tagged events in the subset of data with $LR > 0.86$. We define the raw asymmetry \mathcal{A}_{CP} in each Δt bin by $\mathcal{A}_{CP} = (N_+ - N_-)/(N_+ + N_-)$, where $N_{+(-)}$ is the number of observed candidates with $q = +1$ (-1). Figures 2(c) and 2(d) show the raw asymmetries for two regions of the flavor-tagging parameter r .

The main contributions to the systematic error are due to the uncertainties in the vertex reconstruction (± 0.04 for $\mathcal{S}_{\pi\pi}$ and $^{+0.03}_{-0.01}$ for $\mathcal{A}_{\pi\pi}$) and event fraction (± 0.02 for $\mathcal{S}_{\pi\pi}$ and ± 0.04 for $\mathcal{A}_{\pi\pi}$); the latter includes the uncertainties in $\mathcal{A}_{q\bar{q}}$ and final state radiation. We include the effect of tag side interference [16] on $\mathcal{S}_{\pi\pi}(\pm 0.01)$ and $\mathcal{A}_{\pi\pi}(^{+0.02}_{-0.04})$. Other sources of systematic error are the uncertainties in the wrong tag fraction (± 0.01 for $\mathcal{S}_{\pi\pi}$ and ± 0.01 for $\mathcal{A}_{\pi\pi}$), physics parameters (τ_{B^0} , Δm_d and $\mathcal{A}_{K\pi}$) (< 0.01 for $\mathcal{S}_{\pi\pi}$ and ± 0.01 for $\mathcal{A}_{\pi\pi}$), resolution function (± 0.04 for $\mathcal{S}_{\pi\pi}$ and ± 0.01 for $\mathcal{A}_{\pi\pi}$), background Δt shape (< 0.01 for $\mathcal{S}_{\pi\pi}$ and < 0.01 for $\mathcal{A}_{\pi\pi}$), and fit bias (± 0.01 for $\mathcal{S}_{\pi\pi}$ and ± 0.01 for $\mathcal{A}_{\pi\pi}$). We add each contribution in quadrature to obtain the total systematic error.

We carry out a number of checks to validate our results. The B^0 lifetime is measured with $B^0 \rightarrow \pi^+\pi^-$ candidates. The result is $\tau_{B^0} = 1.50 \pm 0.07$ ps, consistent with the world average value [17]. The CP fit to the sideband events yields no significant asymmetry. We check the measurement of $\mathcal{A}_{\pi\pi}$ using a time-integrated fit and obtain $\mathcal{A}_{\pi\pi} = +0.52 \pm 0.14$, consistent with the time-dependent fit result. We also select $B^0 \rightarrow K^+\pi^-$ candidate events with

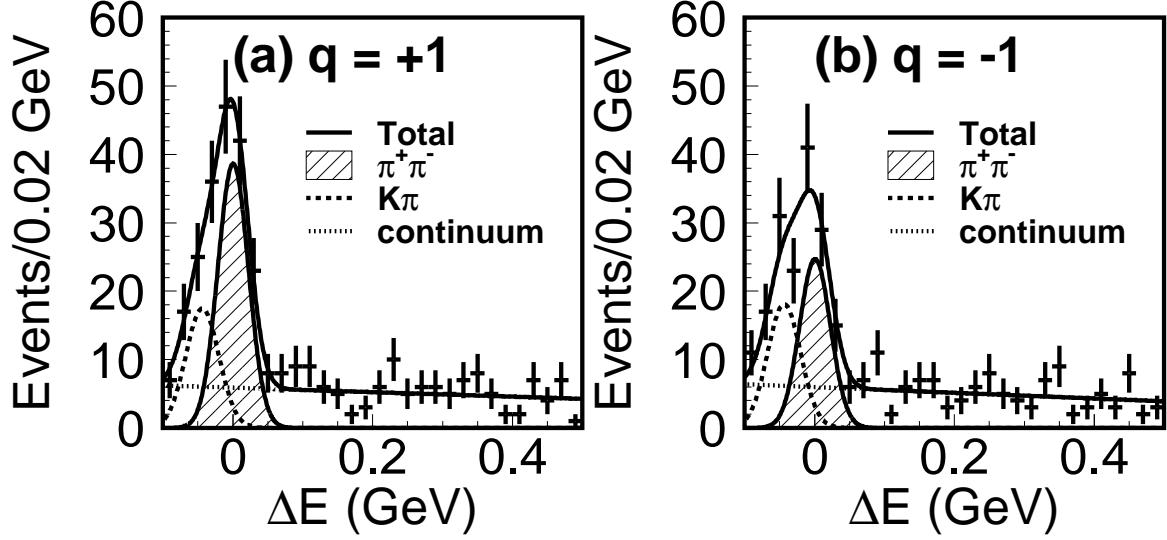


FIG. 3: ΔE distributions in the M_{bc} signal region for the $B^0 \rightarrow \pi^+\pi^-$ candidates with $LR > 0.86$ and $0.5 < r \leq 1.0$ for (a) $q = +1$ and (b) $q = -1$.

charged tracks positively identified as kaons that have a topology similar to the $B^0 \rightarrow \pi^+\pi^-$ signal events. The CP fit to the 4,293 $B^0 \rightarrow K^+\pi^-$ candidates (2,207 signal events) yields $S_{K\pi} = +0.09 \pm 0.08$, consistent with zero, and $A_{K\pi} = -0.06 \pm 0.06$, in agreement with the world average value [13]. With the $K^+\pi^-$ sample, we determine $\tau_{B^0} = 1.51 \pm 0.04$ ps and $\Delta m_d = 0.46 \pm 0.03$ ps $^{-1}$, which are also in agreement with the world average values [17].

To determine the statistical significance of our measurement, we apply the frequentist procedure described in Ref. [4] that takes into account both statistical and systematic errors. The hypothesis of CP symmetry conservation, $S_{\pi\pi} = A_{\pi\pi} = 0$, is ruled out at a confidence level (C.L.) of $1-C.L. = 5.6 \times 10^{-8}$, equivalent to a 5.4σ significance for one-dimensional Gaussian errors. The case of no direct CP violation, $A_{\pi\pi} = 0$, is also ruled out with a significance greater than 4.0σ for any $S_{\pi\pi}$ value.

Figure 3 shows the ΔE distributions for $B^0 \rightarrow \pi^+\pi^-$ candidates with $LR > 0.86$ and $0.5 < r \leq 1.0$ for (a) $q = +1$ and (b) $q = -1$ subsets in the M_{bc} signal region. An unbinned two-dimensional maximum likelihood fit to the $q = +1$ ($q = -1$) subset yields 107 ± 13 (69 ± 11) $\pi^+\pi^-$, 42 ± 9 (43 ± 9) $K^+\pi^-$ and 38 ± 1 (38 ± 1) continuum events in the signal box. The $K^+\pi^-$ and continuum background yields are consistent between the two subsets as expected, while the $\pi^+\pi^-$ yields are significantly different; thus large direct CP -violation in $B^0 \rightarrow \pi^+\pi^-$ decays is manifest in the contrast of the two subsets. These results also support the expectation from $SU(3)$ symmetry that $A_{\pi\pi} \sim -3 \cdot A_{K\pi}$ [18].

We constrain the ratio of the magnitude of the penguin to tree amplitudes $|P/T|$ and the strong phase difference $\delta \equiv \delta_P - \delta_T$ by adopting the notation of Ref. [19], where $\delta_{P(T)}$ is the strong phase of the penguin (tree) amplitude. By using $\phi_1 = 23.5 \pm 1.6^\circ$ [13], we find 95.4% confidence intervals of $|P/T| > 0.17$ and $-180^\circ < \delta < -4^\circ$.

To constrain ϕ_2 , we employ isospin relations [20] and the approach of Ref. [21] for the statistical treatment. We use the measured branching ratios of $B^0 \rightarrow \pi^+\pi^-$, $\pi^0\pi^0$ and $B^+ \rightarrow \pi^+\pi^0$, and the direct CP -asymmetry for $B^0 \rightarrow \pi^0\pi^0$ [13] as well as our measured values of $S_{\pi\pi}$ and $A_{\pi\pi}$ taking into account their correlation. Figure 4 shows the obtained

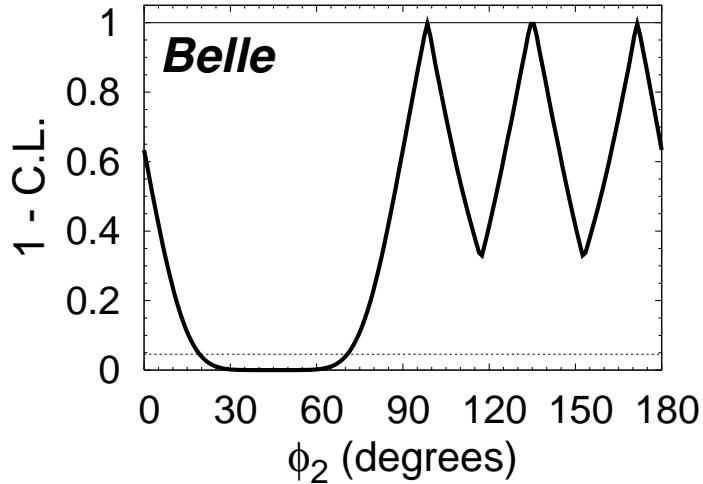


FIG. 4: Confidence level as a function of the CKM angle ϕ_2 obtained with an isospin analysis using Belle measurements of $S_{\pi\pi}$ and $A_{\pi\pi}$. The dotted line indicates C.L. = 95.4%.

C.L. as a function of ϕ_2 . We find an allowed range for ϕ_2 at 95.4% C.L. of $0^\circ < \phi_2 < 19^\circ$ and $71^\circ < \phi_2 < 180^\circ$.

In summary, we have performed a new measurement of the CP -violating parameters in $B^0 \rightarrow \pi^+\pi^-$ decays using a 253 fb^{-1} data sample. We obtain $S_{\pi\pi} = -0.67 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$ and $A_{\pi\pi} = +0.56 \pm 0.12(\text{stat}) \pm 0.06(\text{syst})$. We rule out the CP -conserving case, $S_{\pi\pi} = A_{\pi\pi} = 0$, at the 5.4σ level. We find compelling evidence for direct CP asymmetry with 4.0σ significance. The results confirm the previous Belle measurement of the CP -violating parameters as well as the earlier evidence for direct CP violation in $B^0 \rightarrow \pi^+\pi^-$ decays [4].

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